Effects of 95% Integral vs. FWHM Bandwidth Specifications on Lithographic Imaging

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ABSTRACT

Bandwidth of a laser spectrum is generally specified in terms of the full-width-at-half-maximum (FWHM) metric. Another bandwidth specification is based on the 95% integral energy (E95%) of the spectrum. While providing a more complete information about the spectral shape, E95% bandwidth is very sensitive to small changes in spectral background intensity. In this work, both bandwidth specifications and their effects on aerial image properties are evaluated using computer simulations. Also, in order to obtain a more comprehensive understanding of illumination spectrum effects on lithographic imaging, aerial image sensitivity to the shift of central wavelength and to the change of spectral background intensity is investigated. Results show that the overall shape of the laser spectrum is critically important, and that the E95% metric is more suitable for bandwidth specification.

Keywords: laser bandwidth, chromatic aberration, aerial image

1. INTRODUCTION

Fully-refractive designs for projection systems, commonly used in DUV lithography, put stringent requirements on spectral bandwidth of the illumination light due to chromatic aberrations. These aberrations occur due to the change in index of refraction of optical lens materials with wavelength. Chromatic aberrations can be reduced by certain projection system component designs that use multiple lens materials with different refraction indices. However, if a lens system is made with only one optical material, such as fused silica, chromatic aberrations are inevitable.

As it was shown in our previous publication, even very narrow laser bandwidths can degrade aerial image properties [1]. These results were obtained using computer simulations based on PROLITH/2 software [2]. The bandwidth simulation model was based on the impact of the illumination spectral shape on the chromatic aberration response of the imaging lens. Similarly to the technique proposed by P. Yan et. al., this model assumes linear change of focus due to change of the nominal wavelength [3]. As shown in Figure 1, experimental measurements confirm the linear relationship between focus and wavelength over a fairly extended range [4, 5].

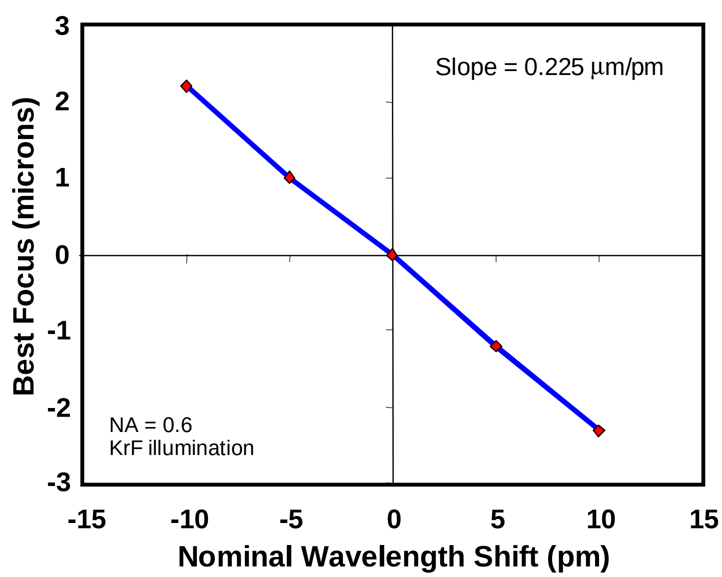

Figure 1. Experimentally measured best focus as a function of nominal wavelength shift [4].

2. LASER BANDWIDTH SPECIFICATIONS

Current production excimer lasers for microlithography have on-board diagnostics that provide bandwidth measurement of the full-width-at-half-maximum (FWHM) (Figure 2a). This metric conveys a general representation of the laser spectrum and its changes at ½ intensity, but it cannot describe the complete spectral shape. Another bandwidth specification, based on the 95% integral energy (E95%) of the spectrum, can be used as a single metric to represent the shape of the spectrum (Figure 2b). This metric corresponds to the spectral width that contains 95% integrated energy of the laser pulse.

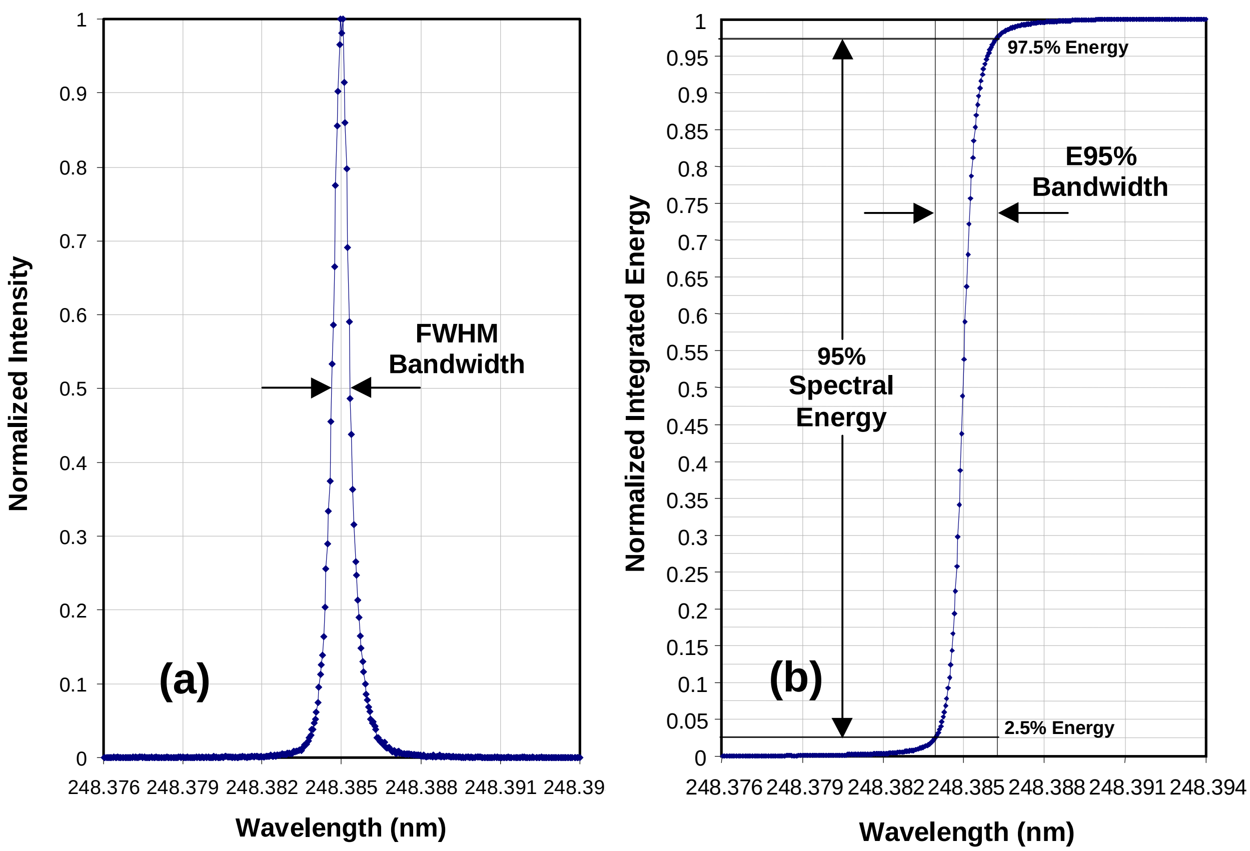

Figure 2. Different specifications of laser bandwidth: **(a)** full-width-at-half-maximum and **(b)** 95% of integrated energy.

Sensitivity of the E95% bandwidth metric to the spectral baseline puts a stringent requirement on the metrology tools. Figure 3 shows the same laser spectrum with three levels of background light. An increase of the relative background intensity level by 0.1% and 0.2% raises the E95% bandwidth by 20% and 57% respectively for a spectrum measured over a 10 pm range. At the same time, the increase of the baseline level does not impact the FWHM bandwidth, which is 0.45 pm for each of the three spectra. Thus, in order to obtain an accurate E95% bandwidth measurement, it is critical to use high-resolution metrology tools with signal to noise ratio of 10^4:1 [6,7].

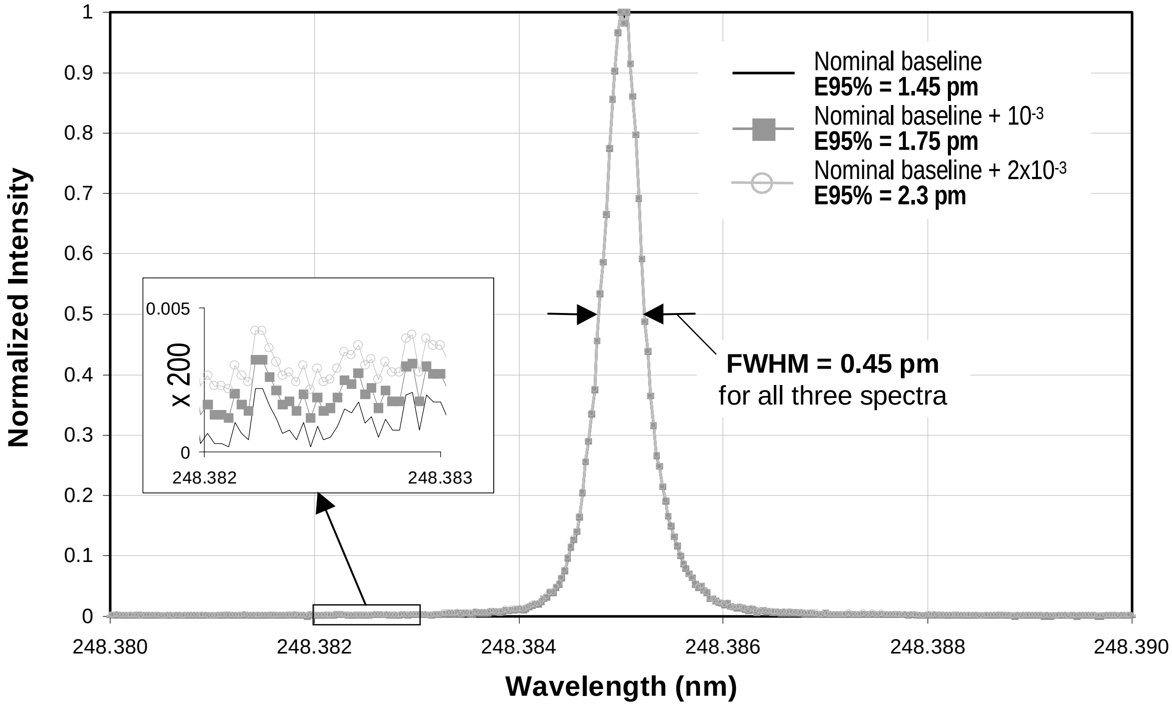

Figure 3. Sensitivity of the E95% bandwidth measurement to the spectral baseline. The inset shows a section of baseline spectra with the scale expanded by 200 times.

3. AERIAL IMAGE FORMATION UNDER POLYCHROMATIC ILLUMINATION

As it was depicted in our previous publication [1], aerial image formation under polychromatic illumination conditions can be described as a weighted incoherent superposition of images created by discrete wavelengths within a defined spectral range. In order to evaluate the impact of any arbitrary or real illumination spectrum on aerial image, it is important to understand the response of image properties to the shift of the central wavelength.

Several studies showed that the predominant effect of central wavelength shift is the change of the image best focus position [4,5]. The rate of focus change due to wavelength shift is primarily dependent on the stepper/scanner projection system design and characteristics such as lens numerical aperture. For simplicity, all studies described in this paper use an experimentally determined linear focus-wavelength slope of 0.225 μm/pm [4].

Aerial image contrast can be used as a metric of an image quality. Image contrast is defined as

$$Contrast = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}},$$

where I_{max} is the maximum and I_{min} is the minimum of the aerial image intensity. The following simulation parameter values were assumed for this simulation study: lens numerical aperture NA of 0.6, partial coherence σ of 0.5, 248.385 nm as a nominal illumination wavelength, isolated and dense lines of 220 nm and 180 nm. Figure 4 depicts image contrast sensitivity of isolated and dense lines to the change of central wavelength over ±20 pm range with a step size of 0.1 pm.

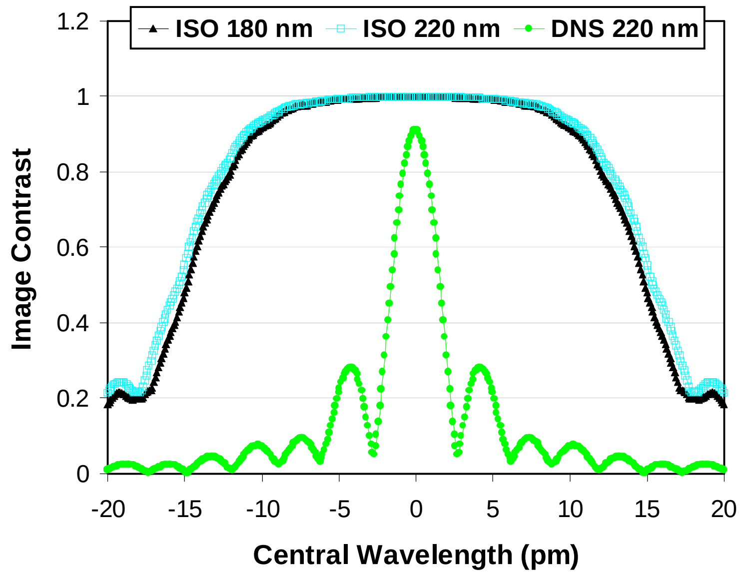

Figure 4. Image contrast response to the shift of the central wavelength for isolated and dense lines.

As shown in Figure 4, shift of the nominal illumination wavelength results in the decrease of the image contrast. Rate of contrast degradation is dependent on imaging system characteristics such as lens design, numerical aperture, target feature size, illumination wavelength, and partial coherence. Also, it is important to notice that the image contrast of isolated and dense lines have fundamentally different dependence to wavelength changes. This effect is a direct result of the difference in through focus imaging of isolated and dense lines.

4. IMPACT OF SPECTRAL BACKGROUND INTENSITY ON AERIAL IMAGE

As shown in Section 2, fairly small changes in the spectral background intensity level significantly impact the measured E95% bandwidth. Also, metrology tools used for spectral measurements have very demanding requirements for baseline assessment at relative intensity levels of 10^{-4}. It is therefore important to understand how the spectral background affects the aerial image properties.

Let's define an arbitrary illumination spectrum that contains a constant background intensity over a certain spectral range, in addition to the central wavelength λ_0 (Figure 5). The aerial image formed by such illumination can be compared to the "ideal" image created by λ_0 only.

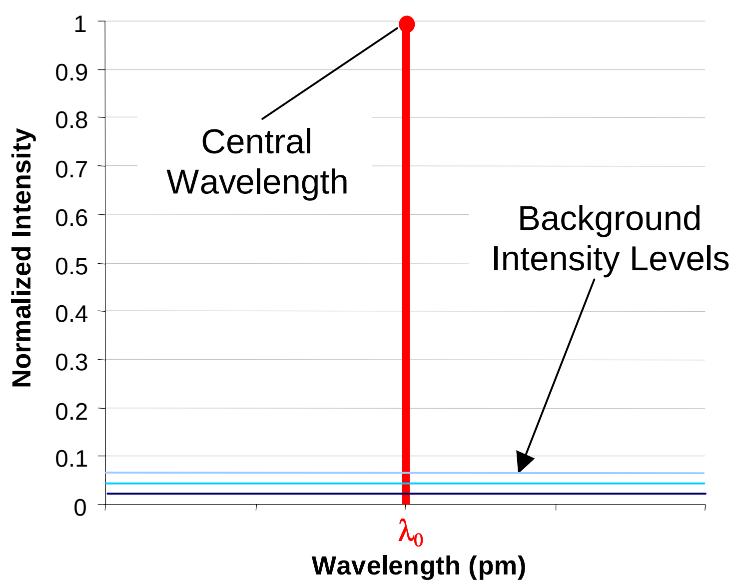

Figure 5. Illumination spectra used in the study of the background intensity and its effects on aerial image.

The impact of the spectral baseline on the final image properties can be studied by changing the level of relative background intensity and its spectral width as input into a simulation model based on PROLITH / 2 software.

In this study, background levels of up to 10^{-2} of relative intensity and spectral width of up to 20 pm were considered. The simulation parameters used in this study are identical to the ones described in Section 3. Aerial image critical dimension (CD) calculations use a threshold level of 32% for isolated and 35% for dense features in order to achieve target linewidths.

Figure 6 shows that aerial image contrast of dense lines degrades extremely quickly with the increase of the spectral background intensity, while contrast degradation of isolated lines is almost insignificant. Contrast loss is a normalized metric and is defined as a ratio of contrasts of a given image to the "ideal" image generated by monochromatic light.

Impact of the background light on the image can be also interpreted in terms of aerial image threshold CD. Interestingly, when using this image metric, response magnitudes of isolated and dense lines are opposite in comparison to the image contrast results. As shown in Figure 7, with the increase of the background intensity level up to 10^{-2}, image CDs of isolated lines rapidly decrease, while dense features print slightly larger. In Figure 7, printed CD bias is defined as the linewidth difference between a given feature and a feature formed by monochromatic light.

Due to the different response of isolated and dense lines to the increase of the background intensity, iso-dense CD bias occurs (Figure 8). Even without consideration of the full laser spectrum, only the relative background intensity of 10^{-3} integrated over a spectral range of 20 pm, generates up to 10 nm image CD iso-dense bias.

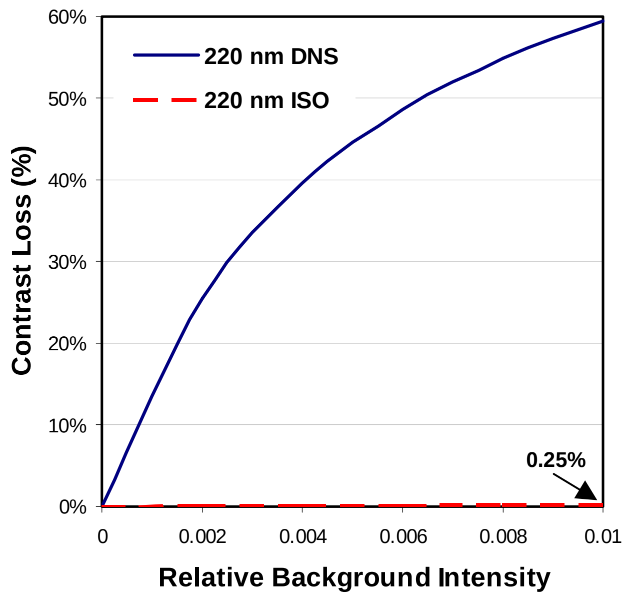

Figure 6. Sensitivity of image contrast of 220 nm isolated and dense lines to the background intensity over 20 pm spectral range.

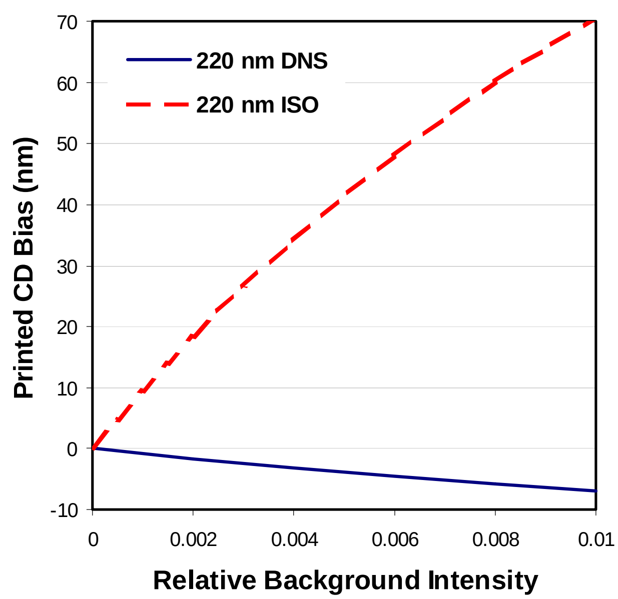

Figure 7. Impact of the spectral background on threshold image CDs of 220 nm isolated and dense lines.

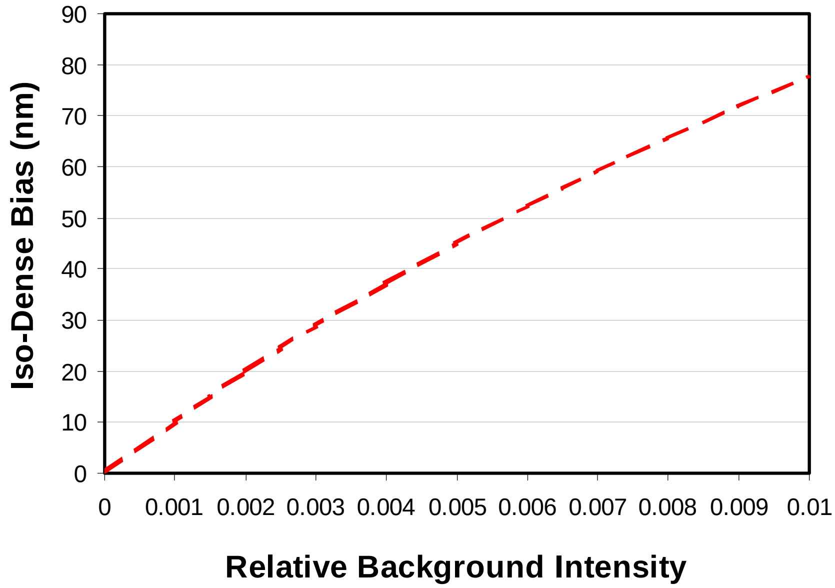

Figure 8. Image CD iso-dense bias of 220 nm lines as a function of the relative background intensity.

Thus, results of this study suggest that illumination spectra with relative background intensity of more than 10^{-4}, integrated over a range of 20 pm, can noticeably degrade aerial image properties and affect image linewidths. This outcome demonstrates the importance of accurate, high-resolution spectral measurements, which can be achieved only with state-of-the-art metrology tools with signal to noise ratio of 10^4:1 or better. This metrology requirement is in line with the requirements imposed by E95% bandwidth measurement results described in the previous section. Unlike the FWHM bandwidth metric, E95% is very sensitive to the changes of spectral baseline level and is more relevant for correlation of this effect to lithographic imaging.

5. RELEVANCE OF FWHM AND E95% BANDWIDTH SPECIFICATIONS TO AERIAL IMAGE PROPERTIES

As shown in section 2, laser bandwidth is commonly specified using FWHM and E95% metrics. It is important to understand how these metrics correlate to image properties and, from this standpoint, which one of them is more suitable for bandwidth specification from a lithographic perspective.

In order to perform this study, four sets of experimentally obtained laser spectra were defined (Figure 9). Each of the sets contains three different spectra. Two of the sets have spectra with constant FWHM bandwidth, while the other two have constant E95%. In each set, the varied bandwidth metric is changed from nominal to approximately 1.6x and 2x values. Keeping these ratios fixed in each of the sets, allows us

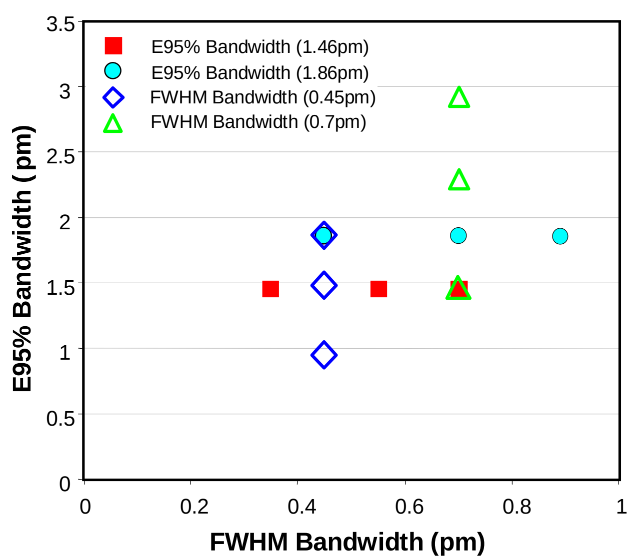

Figure 9. Summary of different spectral conditions used in this study.

to quantitatively compare aerial image results obtained for both bandwidth metrics. In total, ten different spectra were used in this study. In order to obtain all of the necessary bandwidth conditions, some of the spectra were scaled or adjusted.

Simulation parameters used in this study are the following: ***NA*** of 0.7, partial coherence σ of 0.75, KrF illumination at nominal central wavelength of 248.385 nm, isolated 150 nm lines, aerial image threshold level of 31%, full scalar model. Partial coherence was calibrated through the optimization of CD-focus window for the targeted 150 nm isolated lines. A large partial coherence value of 0.75 was chosen because it minimized the linewidth sensitivity of imaged features to focus changes. A chromatic defocus response to central wavelength change of 0.225 µm / pm was used.

Aerial image results obtained were analyzed in terms of properties such as threshold CD, contrast and normalized log-slope. Figure 10 captures through focus CD response of imaged 150 nm isolated lines as a function of bandwidth. Figures 10a and 10c show results for laser spectra that have the FWHM bandwidth fixed at 0.45 pm and 0.7 pm respectively. Figures 10b and 10d depict results for spectra with fixed E95% of 1.46 pm and 1.86 pm respectively.

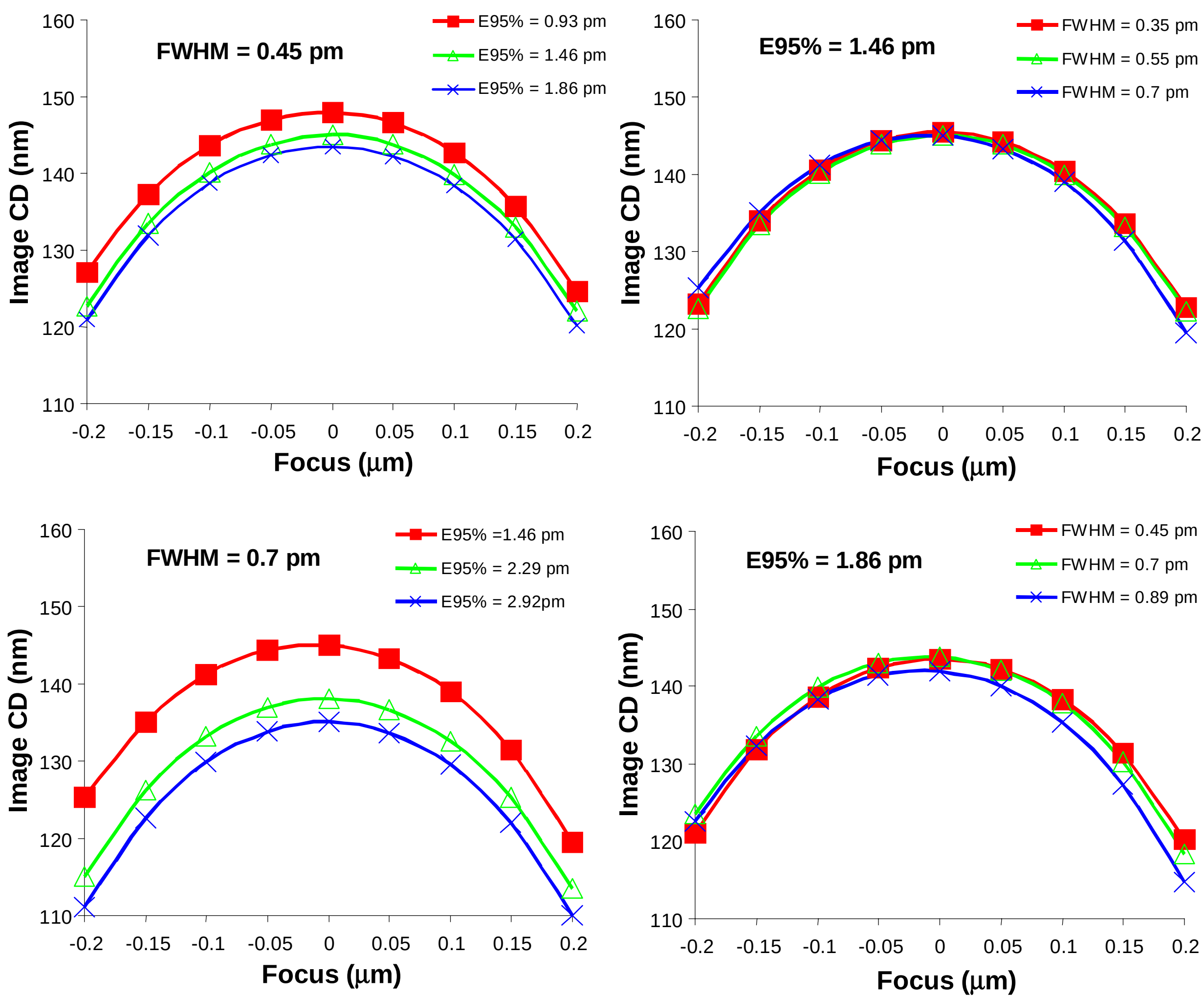

Figure 10. Bandwidth effects on imaging of 150 nm isolated lines through focus. Figures **(a)** and **(c)** depict results for laser spectra with constant FWHM and varied E95%, and figures **(b)** and **(d)** capture results for laser spectra with constant E95% and varied FWHM.

Simulations show that through focus imaging of isolated lines exhibits a clear response to the change of E95% bandwidth of the illumination light, which is not the case when the bandwidth is specified and adjusted in terms of FWHM. It is important to notice that in each of the four cases studied, either E95% or FWHM bandwidth was varied in the same proportion - from nominal to 1.6x and to 2x values.

The results illustrated in Figure 10 can also be interpreted in terms of change of the CD bias. Figure 11 shows the CD bias response at best focus to the change of either E95% or FWHM bandwidth. CD bias is defined as a percent image linewidth change for a given bandwidth compared to the nominal bandwidth condition.

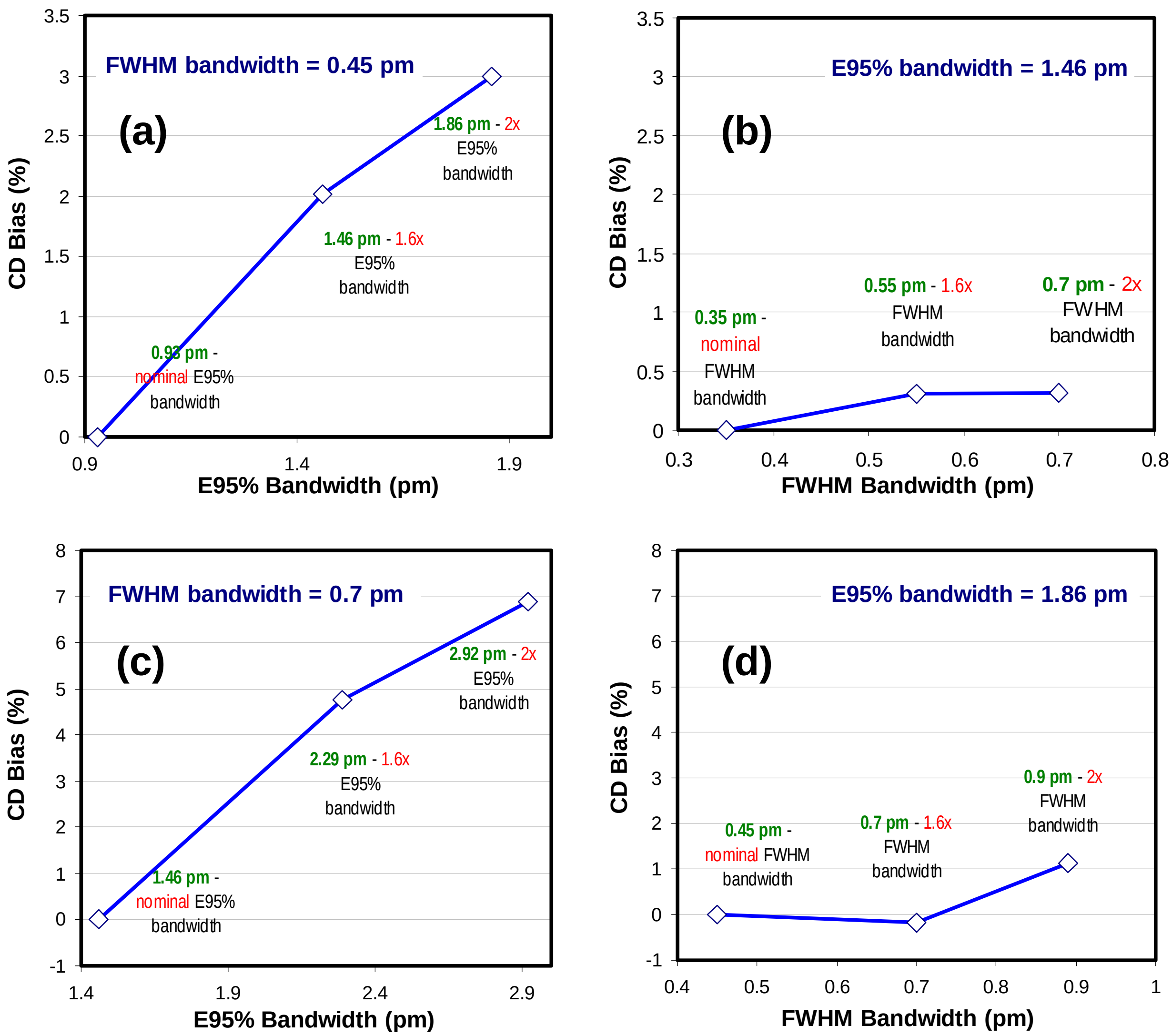

Figure 11. CD bias response of 150 nm isolated lines at best focus to varied bandwidth. Figures **(a)** and **(c)** depict results for laser spectra with constant FWHM and varied E95%, and figures **(b)** and **(d)** capture results for laser spectra with constant E95% and varied FWHM.

Comparing cases with fixed FWHM bandwidth of 0.45 pm (Figure 11a) and fixed E95% of 1.46 pm (Figure 11b), increase of the bandwidth by 100% results in about 3% CD bias when E95% is used as a bandwidth metric versus about 0.3% in the case of FWHM. Results are quite similar when comparing data for fixed FWHM bandwidth of 0.7 pm and E95% bandwidth of 1.86 pm. In this case, doubled E95% bandwidth impacts CD bias by about 7% (Figure 11c) compared to 1% linewidth change for the twice larger FWHM (Figure 11d). It can also be noted that the overall sensitivity of the CD bias to bandwidth grows rapidly with the increase of the nominal E95% or FWHM bandwidth.

Aerial image sensitivity to both bandwidth metrics was also evaluated in terms of image contrast and normalized image log-slope (NILS). Both image contrast and NILS respond to the change of E95% or FWHM bandwidths very similarly to the results obtained for image CDs and CD bias. For example, Figure 12 depicts the through focus sensitivity of the image contrast to the change of either E95% or FWHM bandwidth. At best focus, image contrast decreased by about 3.3% due to doubled E95% bandwidth (Figure 12a), while similar increase in FWHM bandwidth produced only about 0.41% contrast loss.

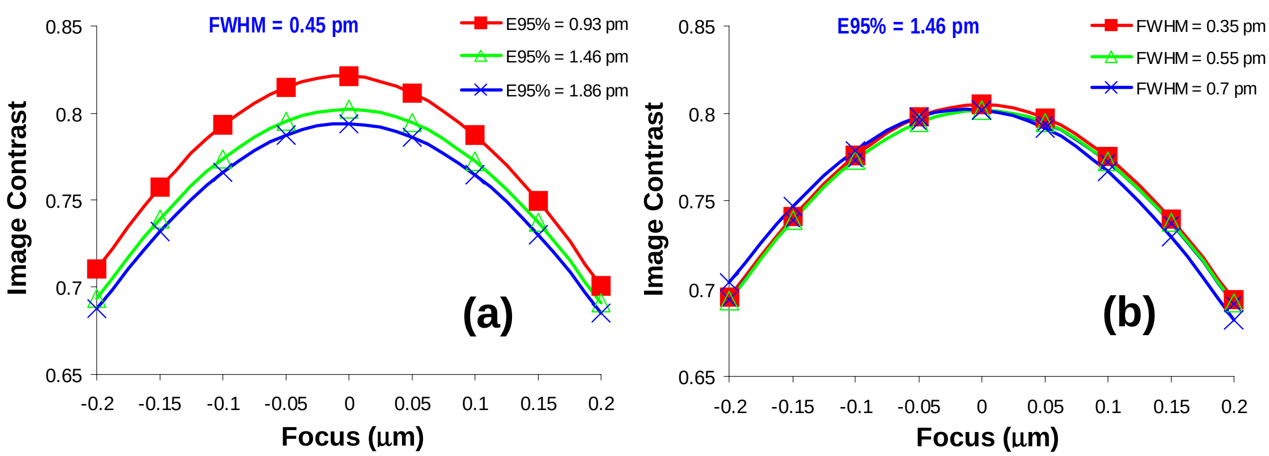

Figure 12. Through-focus image contrast response to the change of E95% **(a)** and FWHM **(b)** bandwidths.

6. SUMMARY AND CONCLUSIONS

FWHM and E95% bandwidth metrics are commonly used to describe the properties of laser spectra. The FWHM specification for bandwidth provides a very coarse description of the laser spectrum, but it can be routinely measured with a high accuracy. However, this metric does not provide any information about the spectral shape and its background. E95% bandwidth specification serves much better for this purpose and is very sensitive to small changes in spectral background intensity level.

It is critical to use high-resolution metrology tools with signal to noise ratio of 10^4:1 or better in order to obtain an accurate measurement of E95% bandwidth. This requirement for metrology is augmented by simulation results showing noticeable degradation of aerial image properties due to spectral background with relative intensity level larger than 10^{-4}. Even 10^{-3} level of spectral background light integrated over 20 pm wavelength range can result in up to 10 nm of iso-dense image CD bias for 220 nm lines. This result is an outcome of the difference in sensitivity of isolated and dense features to wavelength changes.

Comparison of the effects of E95% and FWHM bandwidth on imaging of 150 nm isolated lines was performed using four sets of illumination spectra with fixed E95% or FWHM bandwidths. Overall,

aerial image properties such as image CD, contrast and NILS show nearly an order of a magnitude higher sensitivity to proportional changes of E95% bandwidth compared to their response to FWHM bandwidth. These results suggest that E95% bandwidth is critically important for correlating the spectral performance of the laser to lithographic imaging and is more relevant as a specification than FWHM.

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